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## The Ideal Transformer is a Donut - Part 1

There have been a number of articles recently on the benefits of IE style transformers over Toroid style transformers as they apply to quality audio amplifiers. The following article will be presented over our next 2 Newsletters and was provided by Brad Jolly of Plitron one of the experts in the business of audio transformers. Hopefully this will help provide some much-needed clarity on the subject.

### “Canadian” To The Core

A finished toroidal transformer looks like a donut; its core like a roll of duct tape. There are plenty of alternatives to toroidal transformers. With all the different styles of transformers why should your equipment include a toroid? Based on its benefits, toroidal transformers are the best performers. But let's look at the facts in an earnest (perhaps dull) and somewhat quirky way – very Canadian.

### What's a transformer?

A transformer uses a magnetic field to transfer, or transform, electrical energy. Wire coiled around a magnetic core couples electricity into any other wires coiled around the same core. A power transformer consists of an input coil called a primary winding connected to the source power and an output coil called a secondary winding connected to the load. Power transformers are used in all sorts of applications, but mostly to safely isolate and change electricity from a higher voltage to a lower one.

### History

A toroidal transformer was the first kind of transformer ever wound. Michael Faraday (1791 – 1867 (the year Canada became a country)), British physicist and chemist invented the electric motor, the generator and the transformer. In 1821 he plotted the magnetic field around a conductor carrying an electric current based on Danish physicist Hans Christian Oersted's observations of the existence of the magnetic field in 1819. In 1831 Faraday followed this accomplishment with the discovery of electromagnetic induction and demon-

strated the induction of one electric current by another on a ring of iron – a toroid. He also predicted that gunk that gathers around your battery terminals, but that's another story.

### Ideal Transformer

The ideal transformer would be 100% efficient — no energy loss in transferring power from input to output. An ideal transformer's windings would have zero resistance and no core losses. This transformer's voltage ratio from primary winding to secondary winding would be equal to the turn's ratio of the windings. This figure shows a simple form of this ideal transformer in action. The input of 120V times half an amp equals 60VA. The primary winding of 200 turns is stepped down by a ratio of 10:1 to 12V at 5A, or 60VA. 60VA in, 60VA out is 100% efficient. While we are striving for the ideal, let's look at some related performance goals. Under any condition of loading, the voltage output would not change. Its magnetic field would be completely contained, so it would not radiate any energy. It also wouldn't emit heat or audible noise.

Voltage change with varying conditions of load is specified as load regulation. Because an ideal transformer has zero resistance, its load regulation is 0%. Resistance in windings depends on the number of turns, the length and the thickness of the wire. So, for a given wire gauge, or thickness, the fewer turns required the better.

The ideal transformer has practical applications, such as easy approximations for design purposes but, unfortunately, it's not attainable in the real world. But, as we investigate the various types of transformers, the toroidal transformer will emerge as being clearly the closest to ideal.

### EL, C, R And Toroid

EI, C, R and Toroid are physical types of transformers and the designations generally refer to core shapes. They can also be characterized on an overall performance scale, in the same order, as okay, good, better



and best. Because EI and Toroidal transformers are the most popular of the four, and because the performance benefits and underlying features contrast the most, we'll focus primarily on these two.

**EI:** The EI is so named because an "E" shaped piece of magnetic steel is inserted into one side of a winding bobbin and an "I" shaped piece is butted against it at the other end. This set becomes a layer. The next layer alternates, with the E being inserted from the other side. Many layers are stacked to complete the core. This stack is bolted together in the corners to secure the layers. The E's and I's are alternated layer by layer as they are inserted into the bobbin to distribute the unavoidable gaps. Gaps aren't good for a transformer's efficiency, and gaps are a point of magnetic radiation, which can interfere with surrounding circuits. The gaps between core layers and between E's and I's chatter to make the familiar transformer hum. Their exposure makes the sound worse. Windings on EI transformers usually only cover the center "leg" of the core. This makes for poor core utilization, with about 2/3rds of the core exposed. EI core material is necessarily thicker than the other types described here because of the way in which the core is constructed.

**C:** C cores are made of two "C" shaped groups of laminations formed with strips of magnetic steel. (The "Cs" is really more like "U's", but we'll tow the party line.) The strips of steel are concentrically nested in each "C", and are inserted into each end of two wound bobbins. Where each layer of steel meets its counterpart between the C groups, is a gap. The C core really starts life as an "O" tape-wound core that is slit at various points during its construction to create the dual "Cs". For various reasons, this type of core is better than the EI, but performs poorer than R cores or Toroids.

Gaps in the magnetic circuit make for a lower core efficiency than R or Toroidal cores, but the gaps are wound over which minimizes the magnetic field, performing better than the EI. Core utilization is also better than most EIs with two legs wound on.

**R:** R cores look like rounded rectangles from the top, and are round in the cross-sections. R likely stands for Round. The R core has no gaps in the magnetic path,

making it more efficient than EIs or Cs. Bobbins are first fitted onto the long legs of the R core, and then windings are applied. Core utilization is comparable to C core transformers, but not as good as Toroids.

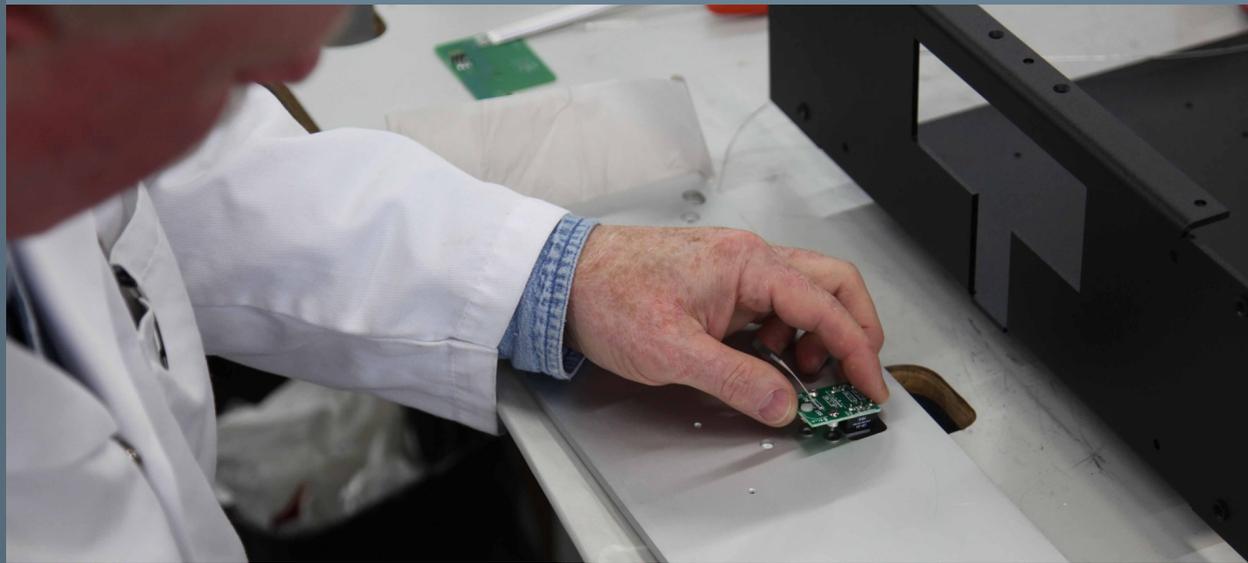
**TOROID:** A donut's shape is a torus. Donuts are toroids. A finished toroidal transformer looks like a donut, but the core really looks more like a roll of duct tape. Toroidal cores, which are made from a continuous strip of steel, wound like a clock-spring, are called tape-wound cores. A tape-wound toroidal core, as constructed, has no gaps. Gaps have their applications, such as inductors, but for the highest performance power transformers, a gapless core works best. Two benefits of no gaps are increased efficiency and reduced stray magnetic fields.

The toroid is the only of the four types to completely utilize its core. This gives a further boost in efficiency and another reduction in stray magnetic fields. Owing to their construction, tape-wound cores benefit from thinner laminations, core materials that offer the best transformer performance.

## CORES

**Magnetic Permeability:** Permeability is the measure of how easily a transformer core can be magnetically energized. A higher permeability allows higher magnetic flux density, which means lower core losses, and fewer turns per volt. The core material, its grain orientation and thickness are factors. Also, the presence of air gaps in the assembly of the core adversely affects permeability in the assembled core. Since fewer turns per volt are required with a higher permeability and higher flux density core, the windings can have lower resistance. Lower resistance means less heat in the windings and better regulation. Also, fewer turns allows for better instantaneous current draw, which is particularly good for audio amplifiers.

**Core Material:** Transformer core materials are chosen for the frequency of the alternating current passing through them. High frequency cores, used in switching power supplies, operate at 20 kHz to over 1 MHz and generally use moulded composite cores of ferrite, or very thin amorphous glass/metal tape-wound materials. What we're focusing on here are power trans-



former applications at utility power frequencies, typically 60 Hz in North America and 50 Hz in most of the rest of the world. At these frequencies, power transformers are made with various types of silicon steel.

**Grain Orientation:** Silicon steels are available as grain oriented or non-grain oriented. Grain oriented steels yield the most efficient cores because they “channel” magnetic energy parallel to their grain structure, so have a higher magnetic permeability.

**Eddy Currents:** Silicon steel is steel with silicon added to make the material less electrically conductive, which helps concentrate magnetic energy by reducing eddy currents. Eddy currents are losses that occur when flowing energy changes from one direction to another as in alternating current (AC).

Eddy currents can be seen when canoeing. A paddle creates pressure during a power stroke that propels the canoe, but also creates swirls that move perpendicular to the movement. This swirl of energy in the water, an eddy current, while pretty, is a waste of energy.

Magnetic fields flowing back and forth in the core of a transformer create swirls of electrical current every time the flow reverses with the AC energy. This conduction of current creates heat. Using silicon steel helps reduce the electrical conductivity of the core, as does insulating between layers. For further reduction of these losses, the material thickness must be reduced. Thinner material, or laminations, makes a shorter path for the electrical current. Tape wound cores can use much thinner laminations than stacked EI cores resulting in much less eddy current loss, so

less electrical current and heat generated, yielding a far more efficient core. Eddy current losses also create mechanical noise.

**Gaps:** The ability to completely contain a magnetic field within a transformer is the key to making it ideal. Any gaps in the magnetic circuit of a core mean the energy must travel through air. Air has a much lower permeability than silicon steel, so cores with gaps have a much lower permeability overall than gapless cores. And lower permeability means lower flux density requiring more turns per volt, so higher resistance windings which hurts regulation and efficiency. Also, having a flux-field travel through air means electrical noise transmitted from the transformer. This electrical noise is picked-up by other circuits within the vicinity and interferes with their operation. This interference causes jitters on CRT monitors and noise in audio systems. Also, air gaps are the main cause of transformer hum. How come transformers hum?

- a) They don't know the tune.
- b) They're not toroidal.

**Core Utilization:** Windings that fully cover the core provide the most ideal performance because they create, transfer and contain a magnetic field most efficiently. A primary winding excites the core, setting-up the magnetic field. The fuller the coverage, the easier it is to do this. Secondary windings draw power from this field. Again, full coverage does this most efficiently. Also, the more completely a core is covered in windings, the better used and contained the flux field is. The better the core coverage the more ideal the transformer.

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